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# In-medium $\rho$ -meson properties in a light-front approach

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**Abstract** Properties of  $\rho$ -meson in symmetric nuclear matter are investigated within a light-front constituent quark model (LFCQM), using the in-medium input calculated by the quark-meson coupling (QMC) model. The LFCQM used here was previously applied in vacuum to calculate the  $\rho$ -meson electromagnetic properties, namely, charge  $G_0$ , magnetic  $G_1$ , and quadrupole  $G_2$  form factors, as well as the electromagnetic radius and decay constant. We predict the in-medium modifications of the  $\rho$ -meson electromagnetic form factors in symmetric nuclear matter.

**Keywords** Light-front, Constituent quark model, Electromagnetic form factors,  $\rho$ -meson, symmetric nuclear matter

## 1 Introduction

One of the main objectives in hadronic physics is to understand the hadron structure in terms of the fundamental degrees of freedom in quantum chromodynamics (QCD), i.e, quarks and gluons. The Standard Model (SM) of elementary particles includes QCD as the strong interaction sector. Although solving QCD is an important part for understanding the SM of the particles physics, it is still a very difficult task (see Refs. [1; 2] for QCD details).

On the other hand, light-front approach is an alternative to calculate observables with the ingredients from QCD [3]. With light-front quantum field theory, it is possible to describe the lower Fock components of the hadronic bound-state wave functions, i.e, mesons and baryons in terms of quarks and gluons [3; 4; 5; 6; 7; 8].

In the present work the previous model for the  $\rho$ -meson in vacuum [9; 10; 11] is used to calculate the in-medium electromagnetic observables such as the electromagnetic form factors, charge  $G_0$ , magnetic  $G_2$ , and quadrupole  $G_2$ , as well as the electromagnetic radius and decay constant, using the plus-component of the current  $J^\mu$  applied in symmetric nuclear matter [12]. (For a review of the in-medium properties of hadrons, see e.g., Refs. [13; 14].) Next, we present the light-front model of  $\rho$ -meson, and briefly review the main ingredients of the model.

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## 2 The Light-front model

The electromagnetic current in the impulse approximation for the spin-1 bound state systems, with the plus component of the electromagnetic current  $J^+$ , is given by,

$$J_{ji}^+ = i \int \frac{d^4k}{(2\pi)^4} \frac{\text{Tr}[\epsilon_j'^\alpha \Gamma_\alpha(k, k - p_f)(\not{k} - \not{p}_f + m)\gamma^+(\not{k} - \not{p}_i + m)\epsilon_i^\beta \Gamma_\beta(k, k - p_i)(\not{k} + m)]}{((k - p_i)^2 - m^2 + i\epsilon)(k^2 - m^2 + i\epsilon)((k - p_f)^2 - m^2 + i\epsilon)} \times \Lambda(k, p_f)\Lambda(k, p_i), \quad (1)$$

where  $m$  is the quark mass, and  $\epsilon_i^\beta$  and  $\epsilon_j'^\alpha$  ( $i, j = x, y, z$ ) are the quadri-vector polarizations, respectively, for the initial state  $\rho$ -meson,

$$\epsilon_x^\beta = (-\sqrt{\eta}, \sqrt{1+\eta}, 0, 0), \quad \epsilon_y^\beta = (0, 0, 1, 0), \quad \epsilon_z^\beta = (0, 0, 0, 1), \quad (2)$$

and for the final state  $\rho$ -meson,

$$\epsilon_x'^\alpha = (\sqrt{\eta}, \sqrt{1+\eta}, 0, 0), \quad \epsilon_y'^\alpha = (0, 0, 1, 0), \quad \epsilon_z'^\alpha = (0, 0, 0, 1), \quad (3)$$

with  $\eta \equiv -q^2/4m_\rho^2 = Q^2/4m_\rho^2 > 0$  ( $q$ : four-momentum transfer).

The electromagnetic current, Eq. (1), is divergent, and in order to turn the Feynman amplitude finite, the regulator function  $\Lambda(k, p)$  is utilized [9],

$$\Lambda(k, p) = \frac{1}{((k - p)^2 - m_R^2 + i\epsilon)^2}, \quad (4)$$

here, the regulator mass  $m_R$ , is chosen to reproduce the experimental value of the  $\rho$ -meson decay constant in vacuum,  $156 \pm 8$  MeV [15].

The vertex with the spinor structure for  $\rho$ - $q\bar{q}$  is modeled by,

$$\Gamma^\mu(k, k') = \gamma^\mu - \frac{m_\rho}{2} \frac{k^\mu + k'^\mu}{p \cdot k + m_\rho m - i\epsilon}, \quad (5)$$

where, the  $\rho$ -meson is on-mass-shell, and its four momentum is  $p^\mu = k^\mu - k'^\mu$ , the quark momenta are  $k^\mu$  and  $k'^\mu$ , and their masses by  $m$  [9; 16].

The light-front  $\rho$ -meson wave function is obtained after the substitution of the on-mass-shell condition,  $k^- = (k_\perp^2 + m^2)/k^+$  in the propagator of the quark that absorbs the photon and in the corresponding regulator,

$$\Phi_i(x, \mathbf{k}_\perp) = \frac{N^2}{(1-x)^2(m_\rho^2 - M_0^2)(m_\rho^2 - M_R^2)^2} \epsilon_i \cdot [\gamma - \frac{\mathbf{k}}{\frac{M_0}{2} + m}], \quad (6)$$

where the polarization state is given by  $\epsilon_i$ . The wave-function corresponds to an S-wave state [4]. The free quark-antiquark mass operator, and the  $M_R$  function are given below,

$$M_0^2 = \frac{k_\perp^2 + m^2}{x} + \frac{(\mathbf{p} - \mathbf{k})_\perp^2 + m^2}{1-x} - p_\perp^2, \quad (7)$$

$$M_R^2 = \frac{k_\perp^2 + m^2}{x} + \frac{(\mathbf{p} - \mathbf{k})_\perp^2 + m_R^2}{1-x} - p_\perp^2,$$

with  $x = k^+/p^+$ .

In the case of spin-1 particles with the light-front approach, the matrix elements of the plus-component of the electromagnetic current,  $J^+$ , is constrained by the angular condition [9; 17; 18]:

$$\Delta(q^2) = (1 + 2\eta)I_{11}^+ + I_{1-1}^+ + -\sqrt{8\eta}I_{10}^+ - I_{00}^+ = 0. \quad (8)$$

With the equation above, it is possible to express the electromagnetic form factors with different linear combinations [9; 17], and eliminate some matrix elements  $I_{m'm}^+$ , ( $m' = 0, 1; m = \pm 1, 0$ ). But, some linear combinations of the electromagnetic matrix elements,  $J_{ji}^+$ , break the covariance as well as the rotational symmetry, because the zero modes contributions or the pair terms [16; 19; 20]. In order to

restore the covariance, it is necessary to add the pair-term contributions or zero modes [9; 16; 19]. The light-front and instant form spin bases are connected by the Melosh rotation matrix (see Ref. [9] for details).

However, in the combinations of the matrix elements of the electromagnetic current from Grach et al. [21], the zero modes are canceled out. This was demonstrated numerically in Ref. [9] and analitically in Ref. [16], since the electromagnetic matrix element of the current,  $I_{00}^+$ , was eliminated by the angular condition [9; 17; 21].

The electromagnetic form factors with the prescription above, are given below in both the light-front spin basis,  $I_{mm'}^+$ , and the instant form spin basis,  $J_{ji}^+$ :

$$\begin{aligned}
G_0^{GK} &= \frac{1}{3} \left[ (3 - 2\eta) I_{11}^+ + 2\sqrt{2\eta} I_{11}^+ + I_{1-1}^+ \right] \\
&= \frac{1}{3} \left[ J_{xx}^+ + 2J_{yy}^+ - \eta J_{yy}^+ + \eta J_{zz}^+ \right] , \\
G_1^{GK} &= 2 \left[ I_{11}^+ - \frac{1}{\sqrt{2\eta}} I_{10}^+ \right] \\
&= J_{yy}^+ - J_{zz}^+ - \frac{J_{zx}^+}{\sqrt{\eta}}, \\
G_2^{GK} &= \frac{2\sqrt{2}}{3} \left[ -\eta I_{11}^+ + \sqrt{2\eta} I_{10}^0 - I_{1-1}^+ \right] \\
&= \frac{\sqrt{2}}{3} \left[ J_{xx}^+ + J_{yy}^+ (-1 - \eta) + \eta J_{zz}^+ \right] .
\end{aligned} \tag{9}$$

In next section, the light-front constituent quark model described above is applied to study the  $\rho$ -meson form factors in symmetric nuclear matter.

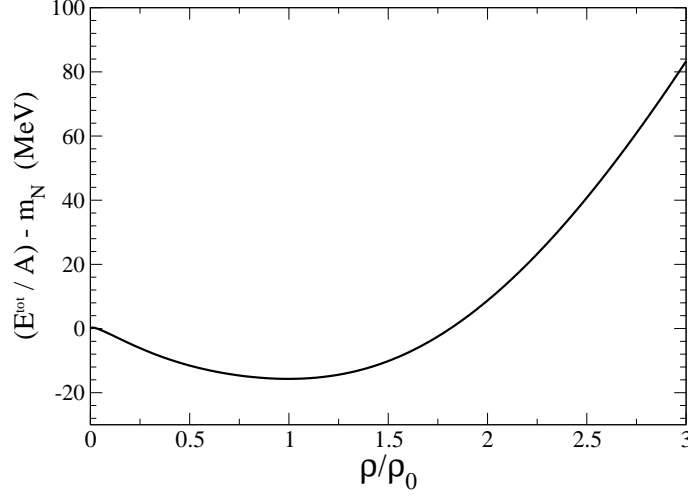
### 3 Rho-meson in-medium

The light-front model for the vector  $\rho$ -meson was developed in Ref. [9] in order to calculate the observables in vacuum. In the present work, we explore that model, to calculate the  $\rho$ -meson observables in symmetric nuclear matter (see Refs. [13; 14] for a review of in-medium quark and hadron properties). For modeling nuclear matter, "Quark-Meson Coupling" (QMC) model is utilized here, and combined with the light-front approach, analogous to that was done for the pion case with symmetric vertex for the pion-quark coupling [12; 22].

The QMC model, which describes nuclear matter based on the quark degrees of freedom, was introduced using MIT bag model by Guichon [23], and Frederico et al. [24] with a confining harmonic potential. The model was successfully applied for finite nuclei [25], and also mesons properties in medium [26]. In the QMC model, because of the surrounding medium, the bound state mesons and baryons are modified, compared with those in vacuum. For some properties calculated for symmetric nuclear matter, we show in Fig. 1 (negative of the binding energy), and summarize in table I.

**Table 1** The MIT bag model (see Ref. [26] for details) quantities and coupling constants, the parameter  $Z_N$ , bag constant  $B$  (in  $B^{1/4}$ ), and the properties for symmetric nuclear matter at normal nuclear matter density  $\rho_0 = 0.15 \text{ fm}^{-3}$ , for  $m_q = 5, 220$  and  $m_q = 430$  MeV. The effective nucleon mass,  $m_N^*$ , and the nuclear incompressibility,  $K$ , are quoted in MeV (the free nucleon bag radius used is  $R_N = 0.8 \text{ fm}$ , the standard value in the QMC model [26]).

$m_q(\text{MeV})$	$g_\sigma^2/4\pi$	$g_\omega^2/4\pi$	$m_N^*$	$K$	$Z_N$	$B^{1/4}(\text{MeV})$
5	5.39	5.30	754.6	279.3	3.295	170
220	6.40	7.57	698.6	320.9	4.327	148
430	8.73	11.93	565.3	361.4	5.497	69.8



**Fig. 1** Negative of the binding energy per nucleon for symmetric nuclear matter, calculated with the vacuum up and down quarks masses,  $m_q = 430$  MeV, with the QMC model [26].

Next, the main ingredients of the QMC model are presented in order to calculate the  $\rho$ -meson properties in medium. For the system of a uniform, spin- and isospin-saturated symmetric nuclear matter, the effective Lagrangian density is given by [26],

$$\mathcal{L} = \bar{\psi}[i\gamma \cdot \partial - m_N^*(\hat{\sigma}) - g_\omega \hat{\omega}^\mu \gamma_\mu]\psi + \mathcal{L}_{\text{meson}}, \quad (10)$$

where  $\mathcal{L}_{\text{meson}}$  is the free meson Lagrangian,

$$\mathcal{L}_{\text{meson}} = \frac{1}{2}(\partial_\mu \hat{\sigma} \partial^\mu \hat{\sigma} - m_\sigma^2 \hat{\sigma}^2) - \frac{1}{2}\partial_\mu \hat{\omega}_\nu (\partial^\mu \hat{\omega}^\nu - \partial^\nu \hat{\omega}^\mu) + \frac{1}{2}m_\omega^2 \hat{\omega}^\mu \hat{\omega}_\mu,$$

and,  $\psi$ ,  $\hat{\sigma}$  and  $\hat{\omega}$  are respectively the nucleon, Lorentz-scalar-isoscalar  $\sigma$ , and Lorentz-vector-isoscalar  $\omega$  field operators, with the effective nucleon mass defined by,

$$m_N^*(\hat{\sigma}) \equiv m_N - g_\sigma(\hat{\sigma})\hat{\sigma}. \quad (11)$$

In the present work, the nuclear matter is in its rest frame. For symmetric nuclear matter with the Hartree mean-field approximation, the baryon ( $\rho$ ) and scalar ( $\rho_s$ ) densities, are calculated as,

$$\rho = \frac{4}{(2\pi)^3} \int d\mathbf{k} \theta(k_F - |\mathbf{k}|) = \frac{2k_F^3}{3\pi^2}, \quad (12)$$

$$\rho_s = \frac{4}{(2\pi)^3} \int d\mathbf{k} \theta(k_F - |\mathbf{k}|) \frac{m_N^*(\sigma)}{\sqrt{m_N^{*2}(\sigma) + \mathbf{k}^2}}, \quad (13)$$

In the equations above,  $k_F$  is the Fermi momentum, and  $m_N^*(\sigma)$  is the value of the effective nucleon mass at a given density, self-consistently calculated with the QMC model [25; 26]. The Dirac equations for the light quark and antiquark, are given by,

$$\begin{aligned} \left[ i\gamma \cdot \partial_x - (m_q - V_\sigma^q) \mp \gamma^0 \left( V_\omega^q + \frac{1}{2}V_\rho^q \right) \right] \begin{pmatrix} \psi_u(x) \\ \psi_{\bar{u}}(x) \end{pmatrix} &= 0, \\ \left[ i\gamma \cdot \partial_x - (m_q - V_\sigma^q) \mp \gamma^0 \left( V_\omega^q - \frac{1}{2}V_\rho^q \right) \right] \begin{pmatrix} \psi_d(x) \\ \psi_{\bar{d}}(x) \end{pmatrix} &= 0, \end{aligned} \quad (14)$$

here, the Coulomb interaction is neglected, because the nuclear matter has the properties adequately described by the strong interactions, also, the SU(2) symmetry for the light quarks ( $m_q = m_u = m_d$ ) is assumed. Because of the symmetric nuclear matter in Hartree approximation,  $V_\rho^q$  is zero.

The bag radius in medium for the  $\rho$ -meson,  $R_\rho^*$ , is determined by the stability condition for the mass of the hadron against the variation of the bag radius [26] (see Eq. (16)), and, the eigenenergies in units of  $1/R_\rho^*$  are given by,

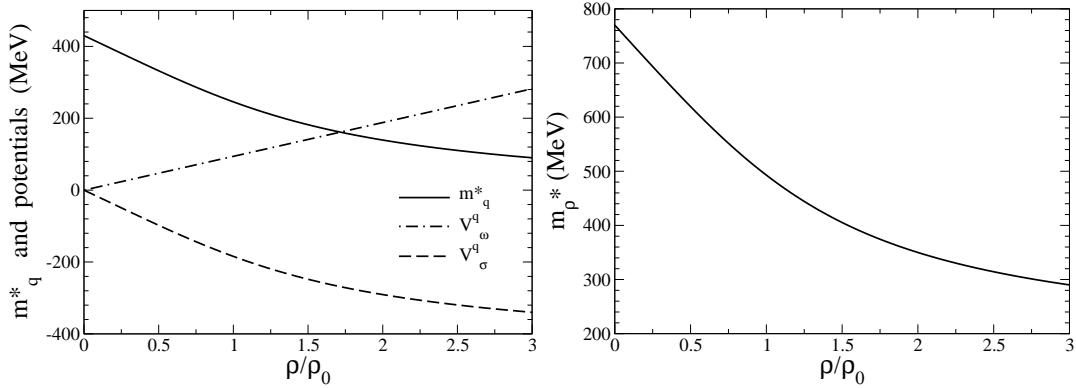
$$\begin{aligned} \begin{pmatrix} \epsilon_u \\ \epsilon_{\bar{u}} \end{pmatrix} &= \Omega_q^* \pm R_\rho^* \left( V_\omega^q + \frac{1}{2} V_\rho^q \right), \\ \begin{pmatrix} \epsilon_d \\ \epsilon_{\bar{d}} \end{pmatrix} &= \Omega_q^* \pm R_\rho^* \left( V_\omega^q - \frac{1}{2} V_\rho^q \right). \end{aligned} \quad (15)$$

The mass of the  $\rho$ -meson in medium is calculated with the expression below,

$$m_h^* = \sum_{j=q,\bar{q}} \frac{n_j \Omega_j^* - z_\rho}{R_\rho^*} + \frac{4}{3} \pi R_\rho^{*3} B, \quad \left. \frac{\partial m_\rho^*}{\partial R_\rho} \right|_{R_\rho=R_\rho^*} = 0, \quad (16)$$

here,  $\Omega_q^* = \Omega_{\bar{q}}^* = [x_q^2 + (R_\rho^* m_q^*)^2]^{1/2}$ , with  $m_q^* = m_q - g_\sigma^q \sigma$ , and  $x_q$  being the lowest bag eigenfrequencies; and  $n_q$  ( $n_{\bar{q}}$ ), is the light-quark (light-antiquark) number. We show in Fig. 2 the calculated in-medium light-quark effective mass and the potentials (left panel), and the effective mass of the  $\rho$ -meson (right panel) in symmetric nuclear matter. In this study, the in-medium input calculated by the QMC model [26], namely, the effective constituent quark mass  $m_q^*$  and effective  $\rho$ -meson mass  $m_\rho^*$ , and the light-front model for the  $\rho$ -meson [9], are utilized in order to calculate the  $\rho$ -meson properties in symmetric nuclear matter.

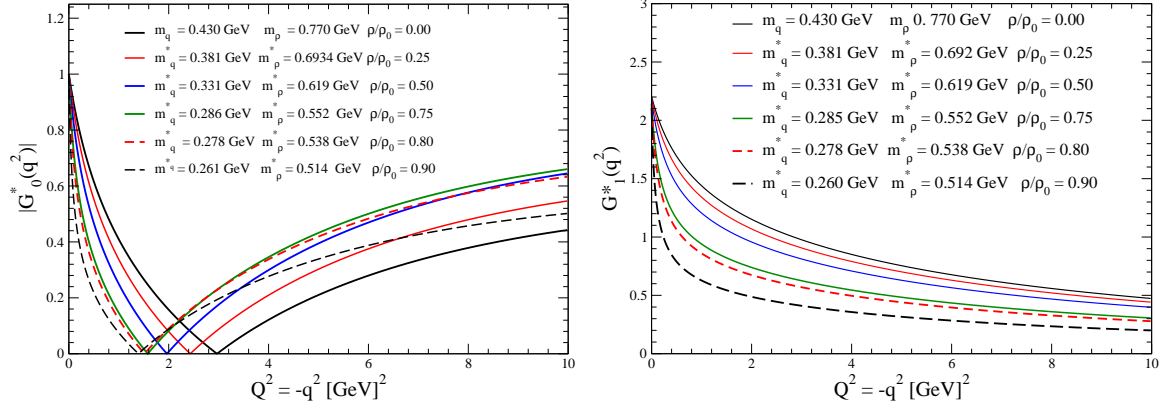
For the constituent quark model with the light-front approach utilized here, the sum of the constituent quark masses forming the bound state  $\rho$ -meson should be larger than the bound  $\rho$ -meson mass for the vacuum case, as well as for the case of the  $\rho$ -meson in medium, since the constituent quark and antiquark masses as well as the effective  $\rho$ -meson mass decrease with increasing nuclear density (see Fig. 2, and expected from the QMC model, similar to that found in the study of the pion case [12]).



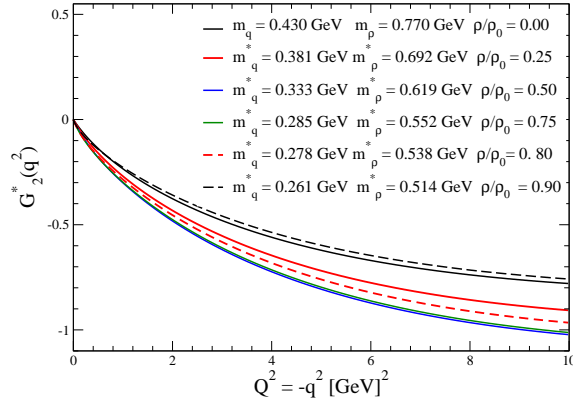
**Fig. 2** Effective constituent light-quark masses and the potentials felt by the quarks (left panel), and  $\rho$ -meson effective mass,  $m_\rho^*$  (right panel), in symmetric nuclear matter calculated by the QMC model [26].

## 4 Results and Conclusions

The LFCQM model scale is obtained by adjusting the value of the experimental  $\rho$ -meson decay constant in vacuum [15; 20], with the quark and antiquark mass values  $m_q = m_{\bar{q}} = 430$  MeV and the regulator mass  $m_R = 3.0$  GeV. We show in Figs. 3 and 4 the calculated  $\rho$ -meson electromagnetic form factors,



**Fig. 3** Electromagnetic charge form factor,  $G_0^*$  (left), and magnetic form factor,  $G_1^*$  (right), both in symmetric nuclear matter, calculate by LFCQM [9] using the in-medium input obtained by the QMC model [26].



**Fig. 4** In-medium  $\rho$ -meson quadrupole electromagnetic form factor,  $G_2^*$ , in symmetric nuclear matter, calculate with QMC model [26] and LFCQM [9].

$G_0^*$ ,  $G_1$ , and  $G_2^*$  in symmetric nuclear matter. The electromagnetic form factors,  $G_0^*$ ,  $G_1^*$  and  $G_2^*$ , are appreciably modified by the medium effects compared with the vacuum case in Figs. 3 and 4, the case  $\rho/\rho_0 = 0$  (see also Ref. [9]).

The charge electromagnetic form factor,  $G_0^*$ , has a zero both in vacuum and in medium in the present model, which is about  $q_{zero}^2 \simeq 3.0 \text{ GeV}^2$  in vacuum [9]. It is very interesting to notice in Fig. 3 (left) that the zero of the charge form factor changes the positions for different nuclear densities due to the medium effects. As increasing nuclear density, the position of the zero shifts to the smaller  $Q^2$ .

The effects of nuclear medium for the magnetic moment of the  $\rho$ -meson is not so strong at  $Q^2 \approx 0$ . In vacuum, the  $\rho$ -meson magnetic moment  $\mu$  is about  $2.20 [e/2m_\rho]$ , and the value agrees with some recent works [27; 28]. At the maximum nuclear density considered here, the magnetic moment has the value of about 2.10, which shows the decrease of 4.5 % relative to the value in vacuum. However, the magnetic form factor decreases as increasing nuclear density and momentum transfer ( $Q^2$ ), as shown in Fig. 3 (right), for six different nuclear densities.

Above the nuclear density  $\rho/\rho_0 = 0.75$ , the quadrupole form factor  $G_2^*$  changes the behavior, and increases (see Fig. 4). The non-zero values for the quadrupole moment is a consequence of the relativistic character of LFCQM. In addition, the reduction rate as increasing  $Q_2^*$  is modified differently because of the medium effects.

In conclusion, we have studied the  $\rho$ -meson electromagnetic form factors in symmetric nuclear matter, charge, magnetic and quadrupole form factors up to  $10 \text{ GeV}^2$ , with a relativistic constituent quark model in the light-front and using the in-medium input obtained by the QMC model. The modifications of the form factors due the medium effects are quite appreciable. The main point of this study is to explore the effects of the medium with well-established model in the literature in the vacuum case [9], and compare with the results with those in symmetric nuclear matter.

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